On the Impact of Beamforming on Interference in Wireless Mesh Networks

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Abstract— For a wireless mesh network with randomly placed devices, we analyze the impact of beamforming on the statistics of the signal attenuation, interference, and SIR between devices. We show that simple random direction beamforming performs equally well as omni-directional transmission if no MAC layer is present. Optimized beamforming between transmitter-receiver pairs yields a much better SIR than omni-directional antennas. If devices are able to eliminate the strongest interferers, either using a MAC protocol or null steering, both beamforming approaches perform much better than omni-directional transmission, i.e., they allow for a given SIR threshold more concurrent transmissions in the network. In fact, applying null steering has the potential to significantly reduce the requirements for the MAC protocol in terms of blocking interferers.

Index Terms— Wireless multihop networks, mesh networks, beamforming, adaptive antennas, interference, medium access.

I. INTRODUCTION AND MOTIVATION

Beamforming antennas enable radio transceivers to focus the radiated power into preferred directions, as opposed to transmitting in all directions. This increases the range of transmissions compared to omni-directional antennas. Beamforming has been thoroughly studied when being applied in base stations of cellular networks. Here, it significantly improves the spatial reuse of radio resources. Current work is analyzing the benefits and challenges if beamforming antennas are deployed on mobile devices as well, in particular if these devices form a multihop mesh network. Especially for relatively static mesh networks, the use of beamforming seems to have performance advantages with feasible implementation efforts.

Most papers in this domain are about the design of medium access control (MAC) protocols [1–6]. Additional work can be found on routing, broadcasting, and multicasting [4, 7–9], as well as throughput capacity [10, 11]. The authors' work has analyzed the impact of beamforming on fundamental topology properties, namely on network connectivity [12] and hop distances between devices [13]. Using accurate radiation patterns of circular and linear antenna arrays, it has been shown that even naive beamforming into a random direction leads to a significant improvement of the network connectivity and reduction of hop distances between devices.

In this follow-up paper, we study whether these improved topology properties come at the price of increased *interference* between devices or not. In this context, we regard interference from two perspectives:

- From the physical (PHY) layer perspective, we ask: Given a receiving device, what is the interference power imposed by surrounding devices that are transmitting at the same time? How many antenna elements are needed at least to cancel out the most critical interferers in the reception pattern?
- From the MAC layer perspective, we apply physical and virtual carrier sensing, assuming thresholds for signal detection and decoding. A received signal is decoded successfully if the power of the signal is larger than a threshold p_1 and the signal-to-interference-ratio (SIR) is larger than a threshold SIR_0. A signal is detected if the received signal power is larger than a lower threshold p_2. We are then interested in the impact of beamforming on the MAC layer functionality.

We study these issues using two different strategies for beamforming:

- If a device has no information about its neighboring devices, a naive and straightforward approach is to beamform into a random direction. We call this communication strategy *random direction beamforming* (RDB). Like omni-directional transmission, it does not require any direction estimation between devices. RDB is especially useful for the startup phase of a device and has low complexity with respect to signal processing.
- If a device does have information about the location of and the channel to its surrounding devices, it can optimize its transmission and reception beamforming. The strategy that a device transmits with maximum gain in the direction of a randomly selected surrounding device is called *neighbor direction beamforming* (NDB).

The paper is organized as follows: Section II explains the used modeling assumptions, including the antenna model, link model, beamforming, and device placement. Section III analyzes the signal attenuation between devices and interprets the impact of beamforming on these results from a MAC layer perspective. Section IV provides an interference and SIR analysis and draws physical and MAC layer conclusions.

A paper closely related to this work is [14]. It studies average values for interference with directional transmission and omni-directional reception, with different numbers of antenna elements. The used antenna model however is rather theoretical, since it assumes always maximum gain in intended transmission and, at the same time, transmission in end-fire direction of the antenna. This would require a manual adjustment of the device.

II. MODELING ASSUMPTIONS

A. Antenna Model

The beamforming antenna we consider in this paper is the *uniform circular array* (UCA). It implies that m antenna elements are arranged on a circle such that the distance Δ between each pair of neighboring elements is fixed. Each antenna element is modeled as an ideal isotropic radiator. The spacing Δ is half the carrier wavelength, i.e., $\Delta = c/(2f)$ with the speed of light $c = 3 \cdot 10^8$ m/s and the carrier frequency f, which we choose as $f = 2$ GHz. We consider the resulting radiation pattern in the far field. In general, beamforming is performed by choosing appropriate values for the amplitude and phase of each antenna element. To limit the degrees of freedom, we choose equal amplitudes for all elements, such that the transmit power p_t is evenly distributed among the elements and each element radiates the power fraction p_t/m. Furthermore we introduce a phase shift between neighboring elements, which remains our only beamforming parameter. This phase shift is then chosen such as to maximize the antenna gain toward the so called *boresight direction* θ_b. The resulting gain pattern $g(\theta)$ constitutes a main lobe, which is pointed toward θ_b, as well as several side lobes with lower gain. As an example, some patterns are depicted in Fig. 1 with $m = 10$ elements for several boresight directions. The exact shape of the pattern depends on θ_b and on the number of elements m. Using less elements will result in a broader main lobe and relatively higher side lobes.

(a) $\theta_b = 90°$ (b) $\theta_b = 50°$
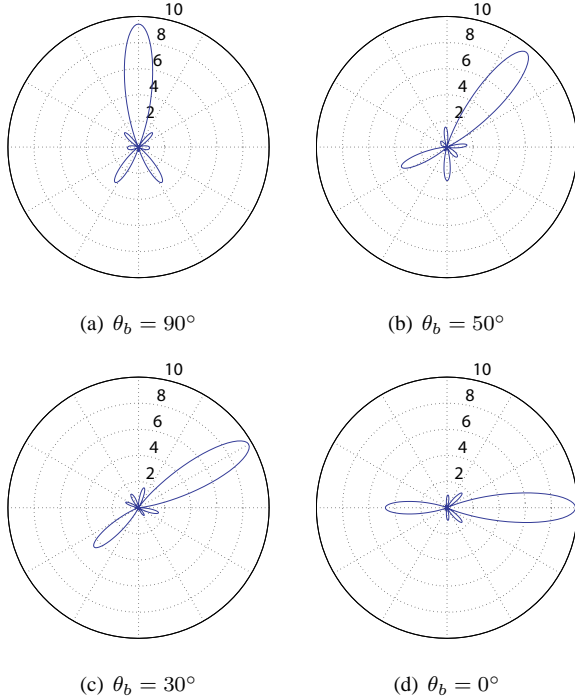
(c) $\theta_b = 30°$ (d) $\theta_b = 0°$

Fig. 1. Gain patterns of UCA with $m = 10$ elements.

B. Link Model

The link between two devices is described by means of the *attenuation* of a signal between them. It is the fraction of the transmission power p_t and reception power p_r and is commonly modeled as

$$a = \frac{p_t}{p_r} = \frac{s^\alpha}{g_t g_r} \cdot \left(\frac{4\pi f}{c}\right)^2 . \qquad (1)$$

The symbol s denotes the distance (in meters) between the sender and receiver in question. The choice of the path loss coefficient α defines the radio environment that we want to model: $\alpha = 2$ represents a free space scenario, while values of $\alpha = 3\ldots5$ are used to model urban environments. The specific value that we are using for all simulations presented in this paper is $\alpha = 3$. The term g_t is the antenna gain of the transmitter beamforming pattern in the direction toward the receiver, while g_r is the antenna gain of the receiver beamforming pattern in the direction toward the sender. The power values are typically given in dBm and the attenuation in dB. In that case, we have $a = p_t - p_r$.

C. Placement of Devices and Beamforming

We consider a square system area of $500 \times 500\,\text{m}^2$ with 50 devices. Each device is placed independently on the system area following a uniform random distribution. The absolute orientation of the antenna array is also randomized and uniformly chosen from $[0, 2\pi[$.

The applied beamforming strategies are illustrated in Fig. 2. In the RDB scenario, each device chooses a random boresight direction uniformly from $[0, 2\pi[$. In the NDB scenario, each device first selects a neighbor that it can reach via omni-directional transmission. It then adjusts its beamforming pattern such that the main lobe points toward this neighbor. In both cases, the resulting beamforming pattern is used for both transmission and reception.

III. ANALYSIS OF SIGNAL ATTENUATION

This section analyzes the signal attenuation between devices. We are interested in the statistics of the attenuation between a device and its neighbors, comparing omni-directional transmission and the two beamforming strategies. This gives us a measure for the potential interference that a device can be exposed to by a single neighbor. From the analysis, we draw some conclusions on the impact of beamforming on MAC layer functionality.

A. Simulation Setup

In a network created by the above modeling assumptions, one device is randomly chosen to act as transmitter. If the RDB strategy is applied, the transmitter randomly selects a sink device from its "directional neighbors," i.e., from the set of devices that it can reach if the devices transmit and receive directionally (Fig. 2(a)). If the NDB strategy is applied, the device toward which the transmitter has steered its main lobe acts as sink. As mentioned above, this sink is always an "omni-directional neighbor." Only in the NDB case, the sink beamforms toward the transmitter for optimized reception (Fig. 2(b)). The remaining devices beamform toward their chosen neighbors, respectively.

(a) Random direction beamforming (RDB)

(b) Neighbor direction beamforming (NDB): beamforming toward an omni-directional neighbor, the receiver under consideration beamforms toward the transmitter.
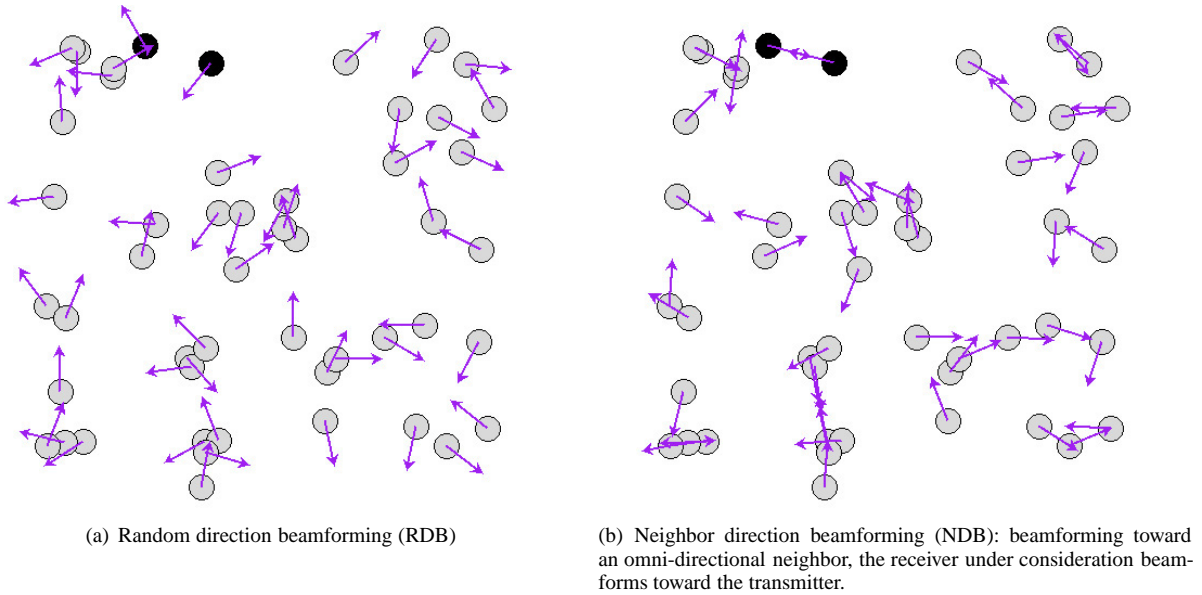
Fig. 2.   Sample topologies. Arrows indicate main lobe directions. The two dark devices indicate one of the 50 transmitter-receiver pairs.

For a chosen sink, the signal attenuation relative to the remaining 48 devices is computed. The attenuation is determined by the path loss, the reception beamforming pattern of the sink, and the transmission beamforming pattern of the remaining devices. After gathering the attenuation values for the given sink, a different device is chosen as transmitter and the steps from above are repeated. After doing so for all devices in the network, $50\cdot48$ attenuation values are gathered. To obtain statistically significant results, we average the relative frequencies of the attenuation histogram over $10,000$ random topologies.

The obtained histogram, having a bin width of 1 dB, is thus a good estimate for the probability density function (pdf) of the signal attenuation, denoted by $f_A(a)$. The cumulative distribution function (cdf) of the attenuation is consequently $F_A(a) = P(A \leq a) = \int_{-\infty}^{a} f_A(a')\, da'$.

B. Simulation Results

Fig. 3 shows the obtained statistics of the signal attenuation. With omni-directional antennas, the attenuation is upper-bounded by a device pair located at opposite corners of the square system area. The pdf $f_A(a)$ can be derived analytically by combining the pdf of the random distance between two devices ($f_S(s)$ [15]) and the path loss model (1).

With beamforming, the pdf is shifted toward high attenuations, beyond the upper bound of the omni-directional case. Such high attenuations occur when the antenna gain of the sink g_r is low in the direction of a neighbor or vice versa. Interestingly, for UCA10, the cdf approaches 1 faster than for UCA4. Giving a closed-form expression for $f_A(a)$ is complex due to the expression for the antenna gain.

The attenuation histograms for RDB and NDB are very similar. This is apparently due to the fact that the spatial distribution of neighbors around a NDB receiver leads to a randomization of the line-of-sight antenna gain, just as RDB does.

C. Implications of Results on MAC Layer

Let us now comment on what we can learn from these attenuation statistics on MAC layer functionality. Typically, MAC protocols for multihop wireless networks are random access protocols operating in a distributed manner and employing two main concepts: First, a device performs *physical carrier sensing* before each transmission attempt, i.e., it listens to the wireless medium to detect whether a transmission is going on or not. Second, optionally, a device performs *virtual carrier sensing* before sending a payload message, i.e., it exchanges explicit control packets with the intended receiver and thus informs potential interferers about the imminent transmission. In IEEE 802.11, physical carrier sensing is done using Clear Channel Assessment (CCA), and virtual carrier sensing is done through the exchange of request-to-send (RTS) and clear-to-send (CTS) messages. In the following, we assume a MAC protocol that applies both physical and virtual carrier sensing.

As mentioned in the introduction, we set two different thresholds for successful signal decoding and detection:

- A received signal can be *decoded*, if its reception power p_r is larger than a threshold p_1; for successful packet reception, the SIR must be larger than a threshold SIR_0.
- A received signal can be *detected*, if its reception power p_r is larger than a threshold p_2, where $p_2 < p_1$.

In accordance with 802.11 standards and products, we assume the following values. The transmit power is $p_t = 20$ dBm for all devices (no power control). The receiver sensitivity for decoding is $p_1 = -81$ dBm. With this, the maximum acceptable signal attenuation for decoding is $a_1 = 101$ dB . The minimum SIR for signal decoding is assumed to be $\text{SIR}_0 = 10$ dB, neglecting noise. The receiver sensitivity for signal detection is assumed to be 10 dB below the decoding threshold, i.e., signals received at a power level of $p_2 = -91$ dBm can be detected by the receiver unit. This corresponds to an attenuation of $a_2 = 111$ dB .
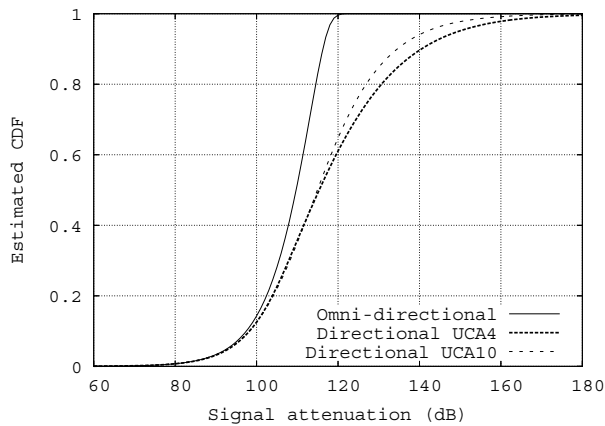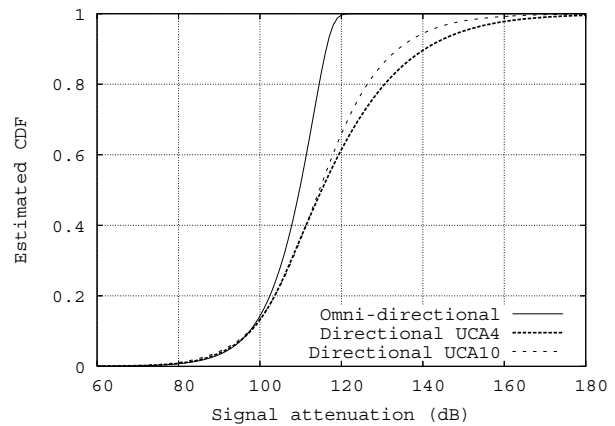
With these thresholds, we can state the following:
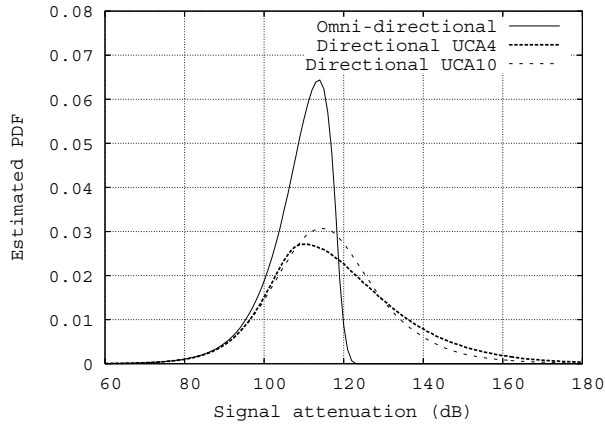
(a) Histogram of the attenuation a using RDB
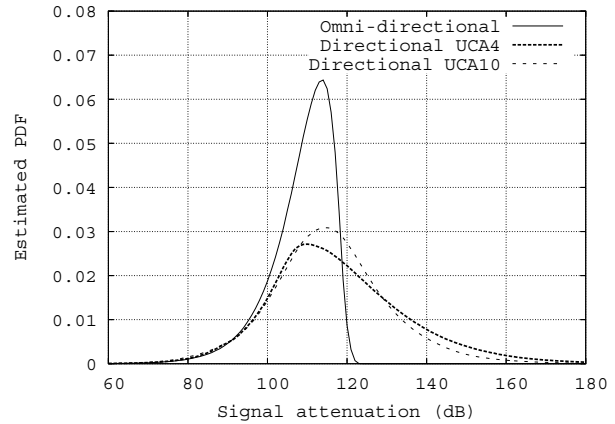
(b) Histogram of the attenuation a using NDB

(c) Cumulative histogram of the attenuation a using RDB

(d) Cumulative histogram of the attenuation a using NDB

Fig. 3. Signal attenuation statistics for omni-directional transmission, RDB, and NDB

- Devices having a low signal attenuation from the prospective transmitter or sink, namely $a < a_1$, can receive explicit MAC signaling and can thus be silenced by RTS/CTS messages. This reduces the spatial reuse, but avoids collisions.
- Devices having an attenuation $a > a_1$ cannot be silenced by control messages but may indeed cause interference. If within the interference range, these devices are referred to as *interference range hidden nodes* (see [16] for a detailed discussion). Physical carrier sensing may detect such an interferer, if the interferer is transmitting during carrier sensing by a device making a transmission attempt, and if $a < a_2$.
- Unless several nodes add up in interference, devices with a signal attenuation $a > a_2$ can be considered to not cause harmful interference.

These statements can now be interpreted in connection with our simulation results on the attenuation statistics with and without beamforming (Fig. 3):

- Low attenuations up to $101\,\text{dB}$, corresponding to high interference, are roughly equally likely for omni-directional and directional antennas (both RDB and NDB). In all cases, a receiver will thus silence about the same number of neighbors by a CTS control packet. Consequently, one

would expect beamforming to not increase spatial reuse with respect to the RTS/CTS handshake. Note that the RTS/CTS scheme does not exploit the increased gain for the desired signal in the NDB case (spatial reservation irrespective of the prevailing SIR).

- Attenuation probabilities in the carrier sensing range between $101\,\text{dB}$ and $111\,\text{dB}$ are reduced by beamforming. The results indicate a reduced need for performing carrier sensing.
- Many nodes are shifted toward high attenuations by beamforming, where even the sum of the interference power of different nodes is unlikely to cause corruptive interference. The MAC layer does not have to deal with these nodes.

In summary, the number of neighbors in the physical carrier sensing range is reduced by beamforming, the number of neighbors in the virtual carrier sensing range is not affected significantly. Modifications of the 802.11 protocol proofed to increase spatial reuse. By the above analysis, it seems that this increase stems from reduced blocking probabilities during physical carrier sensing.

IV. ANALYSIS OF CUMULATIVE INTERFERENCE AND SIR

Having gained some basic insight into the attenuation between two devices, we now study the impact of beamforming

on the cumulative (overall) interference that a sink experiences from all network devices. In this context, we are mainly interested in the following questions: What is the cumulative interference if there is no MAC functionality? How would the cumulative interference change if we eliminate the k most significant interferers by means of signal processing or MAC functionality? What is the SIR at receiving devices?

A. Simulation Setup

We use the same transmitter-sink scenario as in the previous section. All devices transmit with power $p_t = 20$ dBm, i.e., no power control is considered. A randomly chosen transmitter selects a sink from its set of neighbors. For this sink, we sum up the interference of the n least interfering devices, where $n \in \{1, \ldots, 48\}$. Repeating this process for all sinks of $10,000$ random topologies, we obtain a good estimate for the expected interference obtained if $k = 48 - n$ interferers are eliminated. Using $n = 48$ means that all nodes are regarded as interferers, $n = 47$ means that the strongest interferer is eliminated, $n = 46$ that the two strongest are eliminated, and so on. To compute the SIR, we also compute for each sink the signal power received from the intended transmitter.

According to the random process of placing nodes, an interfering node may in rare cases be almost collocated with the receiver. The resulting bias when computing mean linear interference and SIR values has been addressed by computing results for a "typical" interferer. To do so, 50% percentiles where computed for interference and SIR, i.e., the simulation results show the interference/SIR which 50% of the nodes of a given topology see at most/at least. In order to also account for less favored node pairs, we also include 90% percentiles in our results.

B. Simulation Results

The results for the cumulative interference in the RDB and NDB cases are shown in Fig. 4. As already suggested by the results on the attenuation statistics in Fig. 3, RDB and NDB show similar interference levels. If all devices transmit ($n = 48$), the cumulative interference in the beamforming case is in the same order of magnitude as in the omni-directional case. If only weak interferers are considered (low n), the interference is greatly reduced by beamforming.

We also analyze the SIR at receiving nodes, considering the received level of the desired signal. Fig. 5 shows the mean of the SIR taking into account the n weakest interferers. In the RDB case, beamforming has a beneficial effect on the SIR for low to medium n. This benefit gets marginal for n close to 48. In the NDB case, the SIR benefits heavily from the increased directional gain of the desired signal achieved by main lobe alignment. The 90% percentile of the SIR reaches 10 dB already for $n = 43$ in the case of UCA10.

C. Implications of Results on PHY and MAC Layer

Let us now interpret the results on interference and SIR from a physical layer perspective. Therefore we want to discuss the question, to what extend physical layer capabilities can reduce MAC layer requirements and improve the spatial reuse and thus the capacity.

Specifically we want to bring into play the capability of advanced beamforming approaches to cancel out interference from distinct directions. This technique is called "adaptive null steering." An antenna array with m elements can be used to place nulls in the pattern into $m - 1$ distinct directions independently. Choosing $m - 1$ null directions, however, will yield the main lobe to be steered toward an arbitrary direction. Let us therefore assume that we use one of the $m - 1$ degrees of freedom in the beamforming process for main lobe steering. Consequently, we can still place up to $m - 2$ nulls independently, and therefore eliminate the interference of up to $m - 2$ nodes by means of optimized beamforming at the sink node.

Assuming that the sink node can cancel out the $m - 2$ strongest interferers, we can draw some conclusions from the 90% percentile results in Fig. 5. Without a MAC protocol applied, we must consider the SIR value for $n = 48$ in the omni-directional case, yielding a SIR of -24 dB. With the UCA4, the two worst interferers could be canceled out, leaving $n = 46$ interferers. This yields SIR $= -13$ dB for RDB. The UCA10 can be used to eliminate the eight worst interferers, yielding SIR $= -6$ dB for RDB. When applying NDB, the results for the UCA4 and the UCA10 improve with and even without null steering. Without null steering, the UCA4 achieves SIR $= -14$ dB and the UCA10 reaches -11 dB. After nulling the $m - 2$ worst interferers, the results for the NDB case improve to SIR values of -2 dB and 13 dB for the UCA4 and the UCA10, respectively.

Let us now assume $\text{SIR}_0 = 10$ dB and ask the question: how many interferers must be blocked by means of a MAC protocol to achieve this value? In the omnidirectional case, we can conclude from Fig. 5 that no more than $n = 5$ interferers are acceptable, thus at least $k = 43$ nodes must be silenced by the MAC protocol, yielding an extremely sparse spatial reuse. In the RDB case, for both UCA4 and UCA10 up to about $n = 20$ interferers can be tolerated, such that only $k = 28$ nodes must be blocked by the MAC protocol. However, considering that $m - 2$ of those interferers can potentially be canceled out by means of beamforming, we can conclude that the requirement for the MAC protocol reduces to silencing 26 nodes (UCA4) and 20 nodes (UCA10), respectively. Since more nodes can be active at the same time with smart antennas, the spatial reuse can be significantly higher, even using the naive RDB approach. In case of NDB, things improve even more with adaptive antennas. In the UCA4 case, up to about $n = 33$ interferers can be accepted in parallel, so that $k = 15$ interferers must be eliminated. Considering the null steering capabilities of the UCA4, only 13 nodes must be silenced by the MAC protocol. Finally, applying the UCA10 with the NDB strategy, up to $n = 42$ interferers can be tolerated, such that $k = 6$ interferers must be eliminated. However, since the UCA10 has the capability of nulling out 8 interfering nodes, in this case the adaptive antenna capabilities *completely eliminate the need for the MAC functionality* of blocking parallel transmissions.
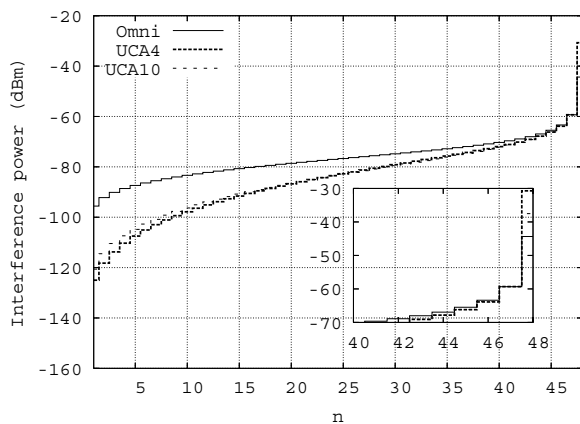
Concluding the discussion of this section, we state that adaptive antennas have the potential to significantly improve the spatial reuse and to significantly lower the requirements for MAC
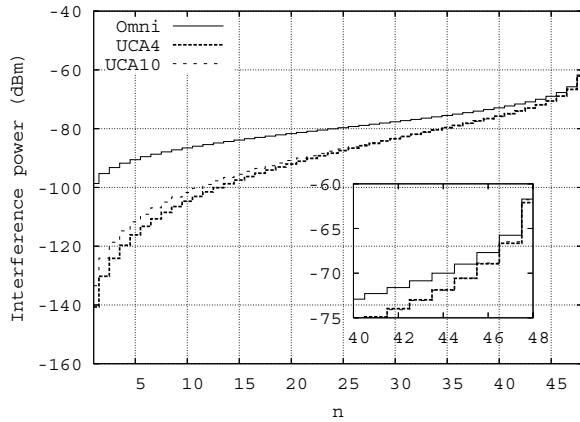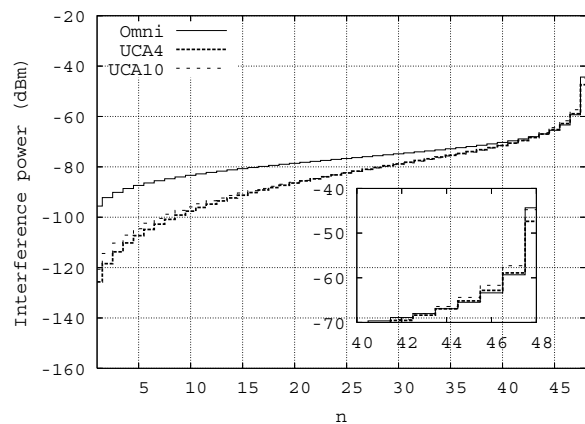
(a) RDB, 50% percentiles
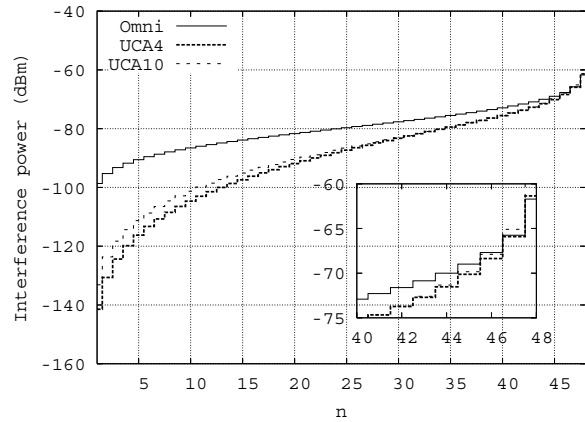
(b) NDB, 50% percentiles

(c) RDB, 90% percentiles

(d) NDB, 90% percentiles

Fig. 4. Interference power at a receiving node caused by the n least interfering nodes, for the two scenarios of Fig. 3.

protocols. To approach this potential, *a lot of further research is required*. Some of the following questions are still open: How does the change of the pattern after null steering change the interference situation? How strong is the degradation of the gain in the boresight direction $g(\theta_b)$ after null steering? How can we design a MAC protocol that silences the right (the strongest) interferers? How do the nodes obtain information about the direction of the strongest interferers?

V. CONCLUSIONS

The starting point for this research was the fact that randomized beamforming improves the level of connectivity in multi-hop mesh networks. We thus asked: Does this improved topology property imply higher or lower inference between nodes? From our simulation-based analysis, we can now give qualitative answers.

If no MAC protocol is employed to coordinate the transmissions of nodes, random direction beamforming performs equally well as omni-directional transmission with respect to interference and SIR. Neighbor direction beamforming yields a much better SIR, since the transmission and reception gains are optimized between transmitter and sink.

If we employ a MAC protocol to eliminate the strongest interferers, both beamforming approaches yield lower interfer-

ence and better SIR than the omni-directional case. In other words, for a given SIR_0, a larger number of concurrent transmitters n is tolerable with beamforming, leading to a higher spatial reuse in the mesh network.

We were also interested in the potential of advanced beamforming with adaptive null steering. We showed, quantitatively for our specific network scenario, how this technique improves the received signal quality, and to what extent it reduces the requirements for medium access control.

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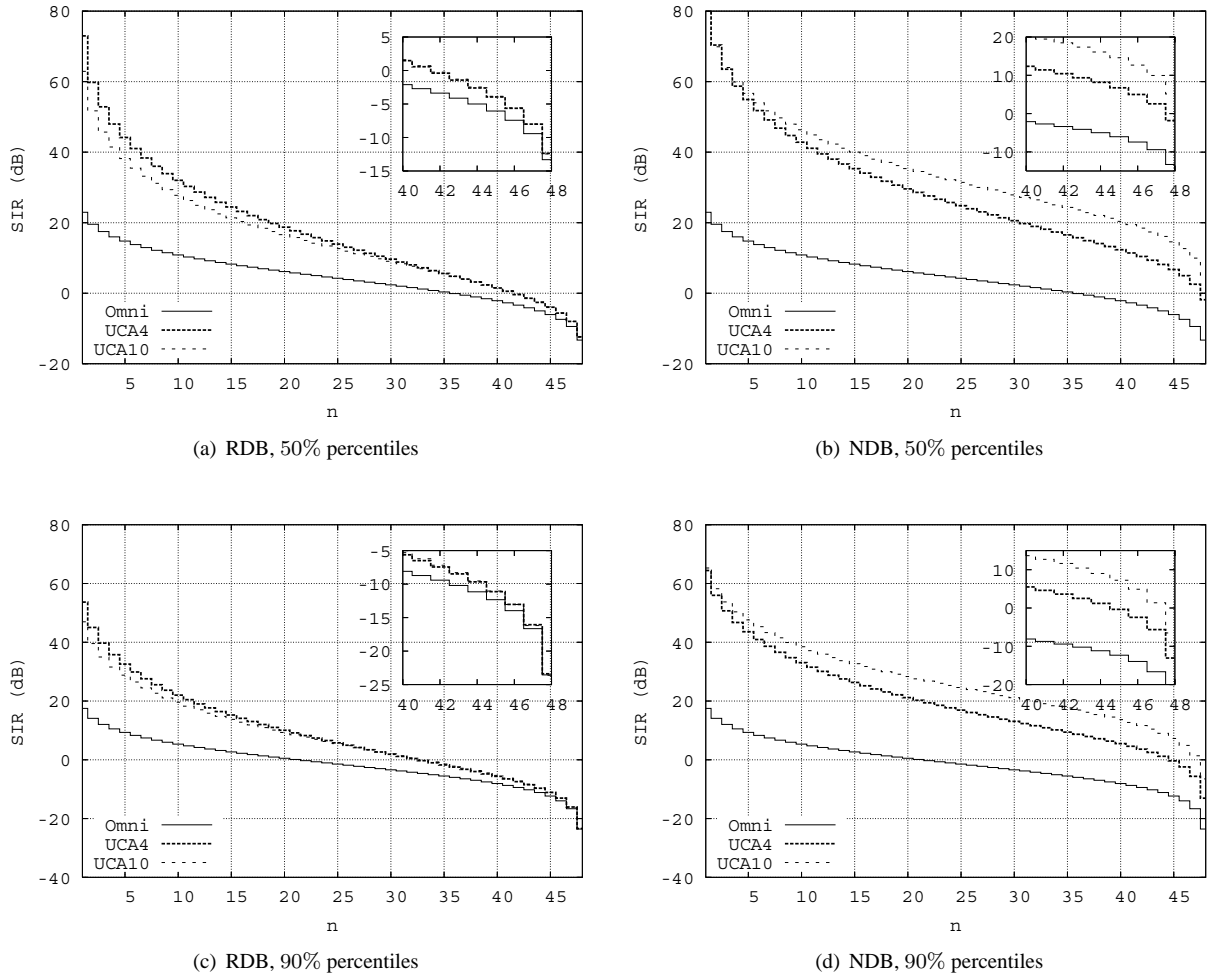
(a) RDB, 50% percentiles

(b) NDB, 50% percentiles

(c) RDB, 90% percentiles

(d) NDB, 90% percentiles

Fig. 5. SIR considering the n least interfering neighbors for the two scenarios of Fig. 3.

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